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A real-time collision avoidance learning system for Unmanned Surface Vessels

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ABSTRACT

A great amount of effort has been devoted to the study on Unmanned Surface Vehicles (USV) due to an increasing demand for their use in a variety of maritime applications. Real-time autonomous collision avoidance system is the pivotal issue here, in which reliable collision risk detection and the adoption of a plausible collision avoidance maneuver play a key role. Existing studies on this subject seldom integrate the COLREGS guidelines, however, and in order to ensure maritime safety, it is of fundamental importance that they should be obeyed at all times. In this paper, we presented an approach to real-time collision avoidance that complies with the COLREGS rules for USV. The Evidential Reasoning (ER) theory is employed to evaluate the collision risks with obstacles encountered and trigger a prompt warning of a potential collision. Then, we extend and adopt the optimal reciprocal collision avoidance (ORCA) algorithm so as to determine a collision avoidance maneuver that is COLREGS compliant. The proposed approach takes into consideration the fact that other obstacles also sense their surroundings and react accordingly, conforming to a practical marine situation when making a decision concerning collision-free motion. A number of simulations have been conducted in order to confirm the validity of the theoretic results obtained.

1. Introduction

USVs are powerful instruments used in a wide variety of maritime missions in civil, military or research applications including oceanography, remote sensing, weapons delivery, force multipliers, environmental monitoring, surveying, anti-submarine warfare, surface warfare, electronic warfare and maritime interdiction operations support, as illustrated in studies [1–4]. All of the missions listed above require safe navigation in open waters. The main challenges relating to this issue include reliable obstacle detection and effective collision avoidance [5]. Unfortunately, relevant research has focused to date predominantly on advanced control system design, for example, [6–8] and with little attention being paid to the field of collision avoidance as illustrated in [9]. The usability and expansibility of USVs are severely constrained in consequence. So as to take full advantage of USVs, an emphasis on obstacle detection and avoidance (ODA) is of paramount importance.

Collision risk assessment is the foundation behind an ODA system. Mou [10] pointed out that the timely and prompt alert of an impending collision is crucial so that a collision can be avoided, thus ensuring maritime safety and a reduction in potential casualties. Collision risk incidence (CRI), in which the probability of a collision with other vessels is evaluated, has three significant characteristics, namely ambiguity, uncertainty and instantaneity. The value of CRI is affected by various factors, among which key elements with a significant impact on CRI are Distance to Closest Point of Approach (DCPA), Time to Closest Point of Approach (TCPA), the distance from the threatening vessel (D), the Relative Bearing (B) and the ratio of speed (K) according to existing literature [11]. The weight method, based on DCPA and TCPA, was adopted early on by Kearon [12] and Imazu [13] in order to estimate the risk of collision. The weight method only takes into account the extent of DCPA and TCPA to obtain the risk. The units of the two factors are in fact inconsistent so that the estimated result is imprecise. With the rapid development of neural networks refer to [14–16], some new approaches in terms of CRI assessment based on neural networks, have been developed, the relevant work can be found in [17,18]. Due to the drawbacks of these neural networks, such as poor generalization ability and the ease with which it falls within a local optimal solution, this

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method is of limited use in practical marine navigation. The research conducted by [19] reveal that fuzzy theory is acknowledged to be the most reasonable approach for the evaluation of CRI, and there has been a successful body of research concerning this particular approach. There are, nevertheless, still some drawbacks restricting the widespread application of this approach owing to the fact that precise membership functions are difficult to establish, with the assessment of CRI being extremely sensitive to this type of function. Different assessments may thus be inferred owing to the disparity of membership functions.

This paper proposes a CRI assessment approach based on the ER theory and aims to provide an accurate estimation of the risk of collision. The ER theory is an analytic approach which can deal with the multiple attribute decision problem, it was first presented by Dempster [20] and subsequently extended by Shafer [21], has extensive applications in many areas. The ER theory has a well-established theoretical foundation and is able both to deal with uncertain information and to take full advantage of multisource information to obtain an accurate estimation. It has moreover been proved by Srivastava [22] that the ER theory is able to achieve fast convergence without a priori probability and conditional probability. Compared with fuzzy theory or neural networks, the ER theory is believed to represent a convincing and reliable algorithm for the evaluation of CRI in consequence of its outstanding performance in terms of dealing with indeterminate and real-time information.

After confirming a potential conflict, the next step is to adopt a timely avoidance maneuver. Previous studies have attempted to resolve this issue; Svec [23], for instance, employed a nominal trajectory planner to generate a collision free trajectory between the current state of a USV and its motion goal and, in the work of Soltan [24], ordinary differential equations were used to define transitional trajectories able to avoid obstacles. Phanthong [25], meanwhile, adopted a numerical solution procedure based on an A* algorithm to compute near-optimal paths; he then used a robust real-time path re-planning technique to avoid moving obstacles. Nevertheless, these studies focused solely on the computation of a collision-free path without respecting CORLEGS compliancy. However, as Statheros et al. [26] report, 56% of all collisions at sea involve a violation of the COLREGS rules. In consequence, it is important for USV to maintain a strict adherence to the COLREGS at all times.

There are a few studies that successfully integrate the COLREGS rules into collision avoidance techniques for USVs. One significant study can be found in the work undertaken by Benjamin [27], who applied Interval Programming in a behavior-based control framework to represent the navigation rules for safe navigation. Tam et al. [28] proposed a deterministic path planning algorithm able to compute a practical and COLREGS compliant navigation path so that output consistency can be maintained. An automatic obstacle avoidance system for USV emerged in relevant literature [9], in which the R-RA* method was developed for path re-planning when a ship is confronted with multiple approaching vessels. The proposed R-RA* algorithm is able to incorporate the necessary COLREGS rules. Similarly, Naeem et al. [1] established a collision avoidance strategy that consists of a real-time path-planning scheme using the biased line-of-sight method and an offline trajectory generation with a DPSS algorithm able to produce COLREGS-compliant paths. Breitsprecher [29] posited a decision rule induction algorithm in order to build a COLREGS knowledge database and implement it to form an expert decision support system. A framework for a decision-action execution model was introduced by Perera in [19] to facilitate intelligent collision avoidance while respecting the COLREGS rules, in which the Fuzzy-Bayesian-based decision/action formulation process was used to avoid a situation in which a complex collision occurred. The author also presented a fuzzy logic-based intelligent decision making system to improve the safety of marine vessels. In this study, the intelligent decision making rules were formulated in accordance with the COLREGS guidelines to avoid collisions [30]. However, most of the previous methods in which the COLREGS rules are taken into account have failed to handle situations in which there is congestion, with the kinematical constraints of USV being ignored. Kuwata et al. [31] put forward a meritorious approach to motion planning in which the Velocity Obstacles (VO) algorithm [32] was adopted to generate a collision-free path while obeying the COLREGS rules. This approach has the advantage of guaranteeing the safe navigation of USV in cluttered environments. However, this approach, based as it is on the assumption that the vessels encountered are passive — in other words, the reactive actions of the encountered vessels are neglected — while, in fact, in an actual marine situation, the encountered vessels also sense their ambience and change their trajectories accordingly. As a consequence, the path generated by this approach may in fact be unreliable.

Inspired by the approach proposed by Kuwata et al., in which the issue of generating a collision-free path while incorporating the COLREGS rules and simultaneously taking into consideration the reactive action of encountered vessels is taken into account, this paper presents a real-time collision avoidance strategy based on a generalized ORCA algorithm [33]. The ORCA algorithm is the extensional formulation of the VO concept. The VO algorithm was first proposed by Fiorini in 1998 and has been successfully used for a variety of applications in order to avoid collisions with moving obstacles, with several modified approaches based on VO being presented in [34–36]. Among these formulations, one significant method is the RVO [34], which can ensure both collision-free and oscillation-free navigation. Furthermore, it takes into account the reactive behavior of the obstacles. Consequently, it is an appropriate method for handling the problem of reactive collision avoidance. This method can, however, only guarantee collision-free navigation under specific conditions. To overcome this limitation Berg et al. [33] defined ORCA to provide a condition appropriate for multiple robots, and which is adopted and extended in this paper in order to achieve reactive collision avoidance.

In this paper, we intend to develop a real-time autonomous collision detection and avoidance learning system that complies with the COLREGs rules for USV. Firstly, the ER theory is adopted to provide an efficient CRI assessment, in which the weights of the elements corresponding to the value of CRI are assigned through the Analytic Hierarchy Process (AHP) method. The ORCA algorithm is then extended to determine a collision avoidance maneuver at the same time as respecting the COLREGs rules. The rest of paper is organized as follows. Section 2 clarifies the problem this paper intends to solve as well as outlining the general procedure for the approach adopted. In Section 3, the CRI assessment approach is explained specifically. A detailed process for the implementation of the COLREGs compliant collision avoidance method is presented in Section 4. Simulated traffic situations are illustrated followed by a discussion and analysis in Section 5 in order to verify the validity of the proposed approach. The paper is finally concluded with suggestions for further avenues of research related to the approach adopted here.

2. Problem statement and general procedure

2.1. Problem statement

The problem considered in this paper is as follows:

The navigation information of the target ships surrounding the USV and constituting a threat of potential collision is treated first of all. This information includes the velocity v,position p and the course c of both target ships and USV, and the distance D between the USV and the target ship. All these information can easily be obtained through the Automatic Identification System (AIS) on board. Next, hypotheses for the near-term waypoint p_i^{goal} are given; these can be acquired through the predetermined path of the USV by using global path planning techniques, for example [37–39]. The purpose of this paper is, thus, the detection of potential collisions followed by a plausible decision concerning avoidance in keeping with the COLREGs rules based on this known information.

2.2. General procedure for the proposed approach

The solution for the problem outlined above is divided into two main sections. The first section involves a collision assessment. This is, then, followed by a section, in which the decision process relative to a collision avoidance maneuver is discussed. The purpose behind the section relating to the collision assessment is, firstly, to calculate the value of the CRI of each target ship threatening the USV according to their navigation information by adopting the ER theory and then making a priority list according to the value of the CRI. After analyzing the encounter situation of each target ship, the generalized ORCA algorithm is employed so as to decide an appropriate avoidance maneuver in keeping with the COLREGs rules and according to the priority list. The general procedure for the proposed approach is shown in Fig. 1.

3. Collision risk assessment

As we have noted in the introductory section, the value of the CRI is the metric evaluating the collision risk with other target vessels with the value of CRI being affected by various kinds of factor. Among these, the key factors with a significant impact on CRI are DCPA, TCPA, D, B and K. The calculation of these factors and their corresponding membership functions are illustrated in this section. As already mentioned, the most important characteristic of CRI is uncertainty, which is mainly caused by a measure error [40]. CRI is also extremely sensitive to the membership function of the corresponding factors, whereas the ER theory is well equipped to deal with uncertain information and obtains an accurate estimation. The ER theory is thus employed together with the AHP method in order to make a precise assessment of the risk of collision.

3.1. Formation of the related membership function

Let $v_{U/T}, c_{U/T.}$ and $(x_{U/T}, y_{U/T.})$ denote the velocity, course and position coordinates of the ships involved, where the subscript $|_U$ and $|_T$ represent the USV and the target ship respectively. Then, the conventional body-fixed coordinate with the origin of coordinate on the USV is employed to calculate the factors related to CRI, $+y$ pointing to the geographical north and $+x$ pointing east. Subsequently, the relative velocity v_{UT} can be derived as $[v_{UT}^x = v_U \sin(c_U) - v_T \sin(c_T) v_{UT}^y = v_U \cos(c_U) - v_T \cos(c_T)]$, and the relative course can thus be obtained as outlined below:

$$c_{UT} = \begin{cases} \tan^{-1}(v_{UT}^x / v_{UT}^y) & (v_{UT}^x \geq 0, v_{UT}^y \geq 0) \\ 90^\circ & (v_{UT}^x \geq 0, v_{UT}^y = 0) \\ 180^\circ + \tan^{-1}(v_{UT}^x / v_{UT}^y) & (v_{UT}^y < 0) \\ 270^\circ & (v_{UT}^x < 0, v_{UT}^y = 0) \\ 360^\circ + \tan^{-1}(v_{UT}^x / v_{UT}^y) & (v_{UT}^x < 0, v_{UT}^y > 0) \end{cases} \tag{1}$$

We can then obtain the DCPA, TCPA, D and based on the above parameters, with the calculation as indicated below:

$$DCPA = D \times \sin(c_{UT} - \theta - \pi) \tag{2}$$

$$TCPA = D \times \cos(c_{UT} - \theta - \pi)/v_{UT} \tag{3}$$

$$D = \sqrt{(x_U - x_T)^2 + (y_U - y_T)^2} \tag{4}$$

$$K = v_T / v_U \tag{5}$$

where θ denotes the true bearing of the target ship and D is the relative distance between the USV and the threatening ship.

As indicated in [41,42], the standard membership function γ corresponding to the factors above are:

$$\gamma_{DCPA} = \begin{cases} 1 & DCPA \leq d_1 \\ \frac{1}{2} - \frac{1}{2}\sin\left[\frac{\pi}{d_2 - d_1}\left(DCPA - \frac{d_1 + d_2}{2}\right)\right] & d_1 < DCPA \leq d_2 \\ 0 & d_2 < DCPA \end{cases} \tag{6}$$

$$\gamma_{TCPA} = \begin{cases} 1 & TCPA \leq t_1 \\ \left(\frac{t_2 - TCPA}{t_2 - t_1}\right)^2 & t_1 < TCPA \leq t_2 \\ 0 & t_2 < TCPA \end{cases} \tag{7}$$

$$\gamma_D = \begin{cases} 1 & D \leq D_1 \\ \left(\frac{D_2 - D}{D_2 - D_1}\right)^2 & D_1 < D \leq D_2 \\ 0 & D_2 < D \end{cases} \tag{8}$$

$$\gamma_B = \frac{1}{2}\left[\cos(B - 19^\circ) + \sqrt{\frac{440}{289} + \cos^2(B - 19^\circ)}\right] - \frac{5}{17}(0 \leq B \leq 360^\circ) \tag{9}$$

$$\gamma_K = {}^{1}/_{1+\frac{2}{K\sqrt{K^2+1+2K\sin C}}} \tag{10}$$

where, refer to [41], the explanation and the calculation of the relevant parameters used in the above expressions are shown in Table 1.

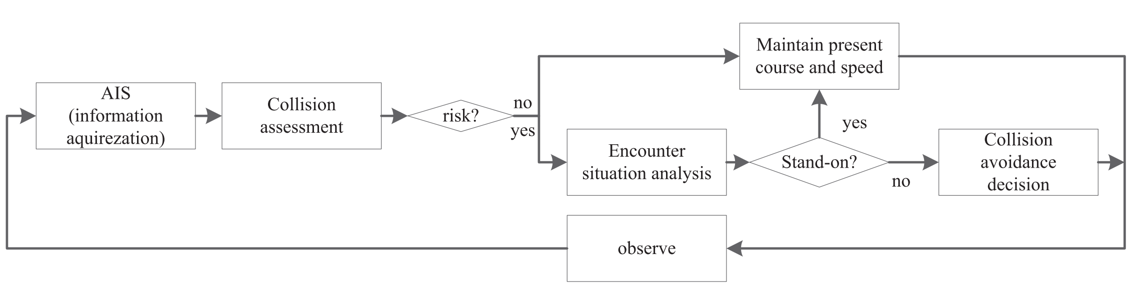

Fig. 1. The general procedure for the proposed system.

Table 1
Explanation of the relevant parameters.

Notation	Explanation	Calculation
d_1	Safe approaching distance	$d_1 = \begin{cases} 1.1-0.2B/180^\circ & 0^\circ \le B < 112.5^\circ \\ 1.0-0.4B/180^\circ & 112.5^\circ \le B < 180^\circ \\ 1.0-0.4(360-B)/180^\circ & 180^\circ \le B < 247.5^\circ \\ 1.1-0.2(360-B)/180^\circ & 247.5^\circ \le B \le 360^\circ \end{cases}$
d_2	Safe passing distance	$d_2 = 2d_1$
t_1	Collision time	$t_1 = \sqrt{D_1^2 - DCPA^2}/v_{oT}$
t_2	Avoidance time	$t_2 = \sqrt{12^2 - DCPA^2}/v_{oT}$
D_1	Distance of action	Determined by the length of the vessel
D_2	Distance of last action	$D_2 = 1.7\cos(B-19^\circ) + \sqrt{4.4+2.89\cos^2(B-19^\circ)}$

3.2. Collision risk assessment based on the ER theory

After we have obtained the membership functions corresponding to the key factors, the next step is to estimate value of the CRI. Due to the remarkable performance of ER theory on dealing with uncertain information, it is quite suitable to employ this algorithm to settle the issue of collision risk evaluation. Yang et al. [43] have developed a recursive ER algorithm based on the basic framework of the ER theory, which combines various pieces of evidence on a one-by-one basis to obtain an accurate result, but this approach is computationally expensive. To overcome this problem, Wang [44] has proposed an analytical ER algorithm that is desirable when handling the issue of aggregating a large number of elements, a procedure that is fairly suitable for CRI assessment. In this subsection, the proposed approach to CRI assessment is outlined based on the analytical ER algorithm.

The AHP method is employed first of all to assign the weight of each factor according to its significance as an estimate for CRI, where Saatys [45] 1–9 point scale is utilized to establish a pairwise comparison matrix to accord with the experience of marine experts. The matrix is shown below, where a_{ij} indicates the degree of importance for criterion C_i compared with C_j and C_i $(i=1\cdots5)$ represents the criteria DCPA, TCPA, D, B and K, respectively. After making the AHP calculation, the weight vector assigned to each factor is:

$$\omega = [\omega_{DCPA}, \omega_{TCPA}, \omega_D, \omega_B, \omega_K] = [0.4535, 0.3604, 0.1481, 0.0527, 0.0393] \tag{11}$$

$$A = \begin{pmatrix} a_{11} & \dots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix} = \begin{bmatrix} 1 & 2 & 4 & 7 & 8 \\ 1/2 & 1 & 3 & 6 & 7 \\ 1/4 & 1/3 & 1 & 5 & 4 \\ 1/7 & 1/6 & 1/5 & 1 & 2 \\ 1/8 & 1/7 & 1/4 & 1/2 & 1 \end{bmatrix} \tag{12}$$

The next step is to calculate the value of CRI by making the ER theory calculation. First of all, we must establish the set of assessment grades of the CRI, denoted by $L_N = (l_1, \dots, l_n, \cdots l_N)$, where N is the number of the level, and the corresponding linguistic members are {'extremely high risk (EH)','high risk (HR)','moderate risk (MR)','slight risk (SR)','safe (S)'} respectively. The risk interval related to each level is $[1-0.8)[0.8-0.6)[0.6-0.4](0.4-0.2](0.2-0]$. The belief degree $\alpha_{n,i}$ of ith factor on each assessment grade can then be obtained by using the similarity calculation, with the definition of the similarity calculation being as follows:

Definition 1. Similarity calculation: let γ_i denote the value of the membership function corresponding to factors f_i, b_{up} and b_{down} represent the boundaries of each risk interval, with the belief degree α being calculated separately according to the following three cases:

Case 1. If γ_i falls into the interval of 'EH' and 'HR', then we can obtain the belief degree α as:

$$\alpha_{n,i} = \gamma_i - b_{down}/b_{up} - b_{down} \tag{13}$$

$$\alpha_{n+1,i} = (b_{up} - \gamma_i/b_{up} - b_{down}) \times \xi_{\rightarrow} \tag{14}$$

where $\xi_{\rightarrow}$ is the adjustment parameter utilized to reflect the subordinate degree of γ_i belongs to l_{n+1} and the calculation of parameter $\xi_{\rightarrow}$, $\xi_{\rightarrow} = (\gamma_i - b_{down})/(\gamma_i - b_{down})$.

Case 2. If γ_i falls into the interval of 'MR', then we can obtain the belief degree α as follows, with the median of 'MR' being represented by $\overline{b}$,

$$\alpha_{n,i} = \begin{cases} \gamma_i - b_{down}/b_{up} - b_{down} & \gamma_i \ge \overline{b} \\ b_{up}\gamma_i/b_{up} - b_{down} & \gamma_i < \overline{b} \end{cases} \tag{15}$$

Case 3. If γ_i falls into the interval of 'SR' and 'S', then we can obtain the belief degree α as:

$$\alpha_{n,i} = b_{up} - \gamma_i/b_{up} - b_{down} \tag{16}$$

$$\alpha_{n-1,i} = (\gamma_i - b_{down}/b_{up} - b_{down}) \times \xi_{\leftarrow} \tag{17}$$

As with $\xi_{\rightarrow}$, $\xi_{\leftarrow}$ also represents the adjustment parameter, which is the reflection of the subordinate degree of γ_i belongs to l_{n-1}, and $\xi_{\leftarrow} = (b_{up} - \gamma_i)/b_{up} - b_{down})$.

After this, by making the following calculation with respect to the ER theory, we can obtain the confidence degree vector $C = \{\lambda|l_1, \dots, \lambda|l_n, \dots, \lambda|l_N, \lambda_{U,n}\}$ of a particular threatening vessel, where $\lambda|l_n$ denotes the confidence degree on the assessment grade l_n.

$$m_{n,i} = \omega_i \times \alpha_{n,i} \tag{18}$$

$$\overline{m_{U,i}} = 1 - \omega_i \tag{19}$$

$$\widetilde{m_{U,i}} = \omega_i \times \left(1 - \sum_{n=1}^{N} \alpha_{n,i}\right) \tag{20}$$

$$K = \left[\sum_{n=1}^{N} \prod_{i=1}^{5} (m_{n,i} + \overline{m_{U,i}} + \widetilde{m_{U,i}}) - (N-1) \prod_{i=1}^{5} (\overline{m_{U,i}} + \widetilde{m_{U,i}})\right]^{-1} \tag{21}$$

$$m_n = K\left[\prod_{i=1}^{5} (m_{n,i} + \overline{m_{U,i}} + \widetilde{m_{U,i}}) - \prod_{i=1}^{5} (\overline{m_{U,i}} + \widetilde{m_{U,i}})\right] \tag{22}$$

$$\widetilde{m_U} = K\left[\prod_{i=1}^{5} (\overline{m_{U,i}} + \widetilde{m_{U,i}}) - \prod_{i=1}^{5} (\overline{m_{U,i}})\right] \tag{23}$$

$$\lambda|l_n = m_n/1-\overline{m_U} \tag{24}$$

$$\overline{m_U} = K\left[\prod_{i=1}^{5}(\overline{m_{U,i}})\right] \tag{25}$$

$$\lambda_{U,n} = \widetilde{m_U}/1-\overline{m_U} \tag{26}$$

where $m_{n,i}$ is the basic probability assessment of factor f_i on grade l_n, and $\overline{m_{U,i}}$ is the uncertainty caused by the influence of the other factors besides f_i when assessing the value of CRI. The parameter $\widetilde{m_{U,i}}$ provides scope for the resolution of conflict and K denotes the normalization constant. Lastly, m_n is the overall basic probability assessment in which all of the factors are integrated, while $\widetilde{m_U}$ and $\overline{m_U}$ are the overall uncertainty that brings together all of the factors.

Finally, we must deduct the CRI of a particular threatening vessel by carrying out the explicit calculation, of which the definition is shown below:

Definition 2. Explicit calculation:

$$CRI = \left(\sum_{n=1}^{N}\lambda|l_n \times \alpha(l_n) + (\lambda_{U,n}/N) \times \sum_{n=1}^{N}\alpha(l_n)\right) \times 0.25 + 0.5 \tag{27}$$

where $\alpha(l_n)$ denotes the risk representation value of grade l_n. In this paper the corresponding risk representation value of each grade is set as $\alpha(l_1, \ldots, l_n, \cdots l_N) = [-2, -1, 0, 1, 2]$.

4. COLREGS compliant collision avoidance method

As we have explained previously, the purpose of this paper is to make a plausible decision concerning collision avoidance that is COLREGs compliant, with the reactive avoidance action of the threatening vessel being simultaneously taken into account. The attendant methodology will be elaborated later in this section. Firstly, a brief overview of the three primary encounter situations presented in the COLREGs rules — namely, circumstances in which an oncoming vessel is encountered head-on, the paths of both vessels cross each other or a situation that involves overtaking occurs. In accordance with the encounters stipulated in the COLREGs, the anticipated action of both the vessels potentially involved in a collision is defined as shown in Table 2, with the corresponding regions illustrated in Fig. 2.

4.1. Generalized ORCA algorithm

In this paper, the generalized ORCA algorithm is utilized to address the issue of reactive collision avoidance in accordance with the COLREGs, with the generalized ORCA algorithm being explained in detail in this section. As illustrated in the instructions, the ORCA algorithm is an extension of the VO algorithm, the concept of which is shown below.

Let A and B represent the two vessels involved in a mutual collision situation located in p_A and p_B, proceeding with velocity v_A and v_B respectively. We use the symbol $\oplus$ to denote the Minkowski sum operation, with $-O$ denoting the object O reflected in its reference point. $\gamma(\mathbf{p},\mathbf{v}) = \{\mathbf{p}+t\mathbf{v}|t \geq 0\}$ represents the ray starting at point p and pointing in the direction of v. The definition of the velocity obstacle is then shown below:

Table 2
Encounters and related information.

Encounter	Region	Anticipated action for own ship	Anticipated action for other vessel
Head-on	A	Alter course to starboard	Alter course to starboard
Crossing	B	Give way	Stand on
	D	Stand on	Give way
Overtaking	C	Stand on	Keep out of the way of own ship

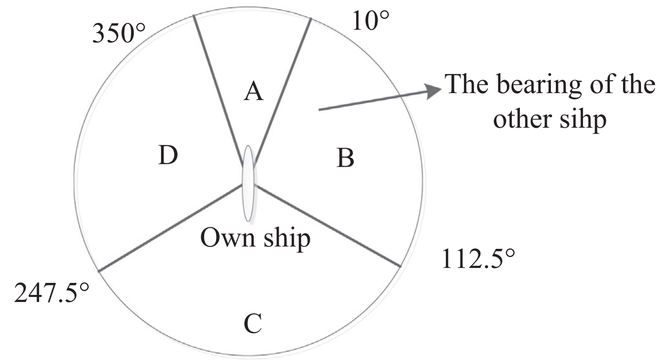

Fig. 2. An illustration of the encounters according to COLREGs.

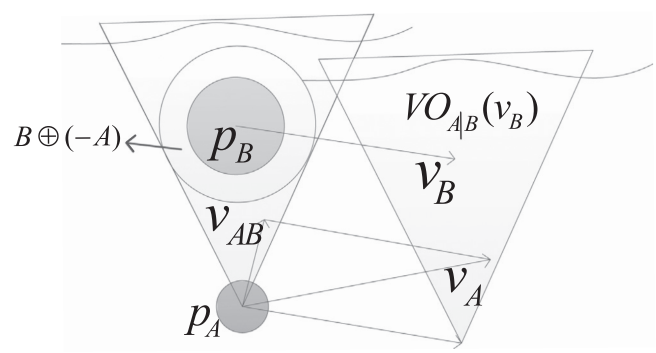

Fig. 3. The velocity obstacle $VO_{A|B}(v_B)$ of B to A.

$$VO_{A|B}(\mathbf{v_B}) = \{v_A^{new}|\gamma(\mathbf{p_A},\mathbf{v_{AB}}) \cap B \oplus -A \neq \varnothing\} \quad \mathbf{v_{AB}} = \mathbf{v_A} - \mathbf{v_B} \tag{28}$$

If $\mathbf{v_A^{new}} \in VO_{A|B}(\mathbf{v_B})$, the two vessels will end up in a collision, while if $\mathbf{v_A^{new}}$ is outside the region of $VO_{A|B}(\mathbf{v_B})$ (see Fig. 3) a collision will not occur. The VO algorithm is an efficient way of avoiding collisions with moving obstacles, but, in their work on the concept behind the RVO algorithm, Berg et al. have pointed out that VO algorithm may cause undesirable and unrealistic oscillations [34]. This approach also takes into account the reactive reaction of both the agents involved in the potential collision by implicitly assuming that both agents make similar calculations to avoid a collision and each one takes an equal share in the effort to avoid a collision. The formation of the RVO is as follows:

$$RVO_{A|B}(\mathbf{v_B}) = \left\{\mathbf{v_A^{new}}|2\mathbf{v_A^{new}} - \mathbf{v_A} \in VO_{A|B}(\mathbf{v_B})\right\} \tag{29}$$

The region of $RVO_{A|B}(\mathbf{v_B})$ can be interpreted geometrically as $VO_{A|B}(\mathbf{v_B})$ that is translated such that its apex lies at $(\mathbf{v_A}-\mathbf{v_B})/2$. If A chooses a new velocity outside $RVO_{A|B}(\mathbf{v_B})$, then the collision can be avoided and no oscillation will occur. Nevertheless, the above formulation only guarantees a collision-free situation under specific conditions. A new principle for ORCA was presented in [33] to overcome this limitation. The definition of ORCA is as follows:

$$ORCA_{A|B}^{\tau} = \left\{\mathbf{v_A^{new}}\left|\left(\mathbf{v_A^{new}} - \left(\mathbf{v_A} + \frac{1}{2}\mathbf{u}\right)\right)\bullet\mathbf{n} \geq 0\right.\right\} \tag{30}$$

$ORCA_{A|B}^{\tau}$ is the half-plane region delimited by the line perpendicular to $\mathbf{u}$ through the point $\mathbf{v_{AB}}+\mathbf{u}/2$, where $\mathbf{n}$ is the outward normal of the boundary of $VO_{A|B}(\mathbf{v_B})$ at point $\mathbf{v_{AB}}+\mathbf{u}$, and $\mathbf{u}$ is

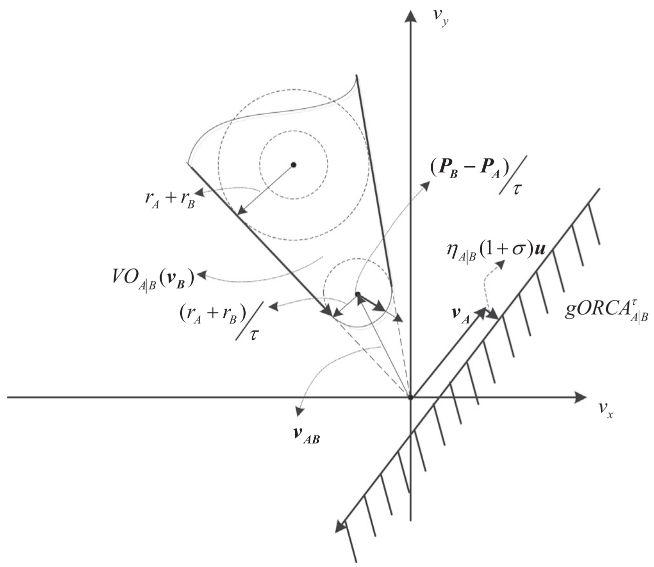

Fig. 4. The region of $gORCA^{\tau}_{A|B}$ is the permitted velocity set for A to avert collision with B.

the vector from $\mathbf{v_{AB}}$ to the closet point on the boundary of $VO_{A|B}(\mathbf{v_B})$, namely, $\mathbf{u}$ is the smallest change required to the relative velocity $\mathbf{v_{AB}}$ to avoid a collision within a τ time interval, with the formation of $\mathbf{u}$ being as follows:

$$\mathbf{u} = \left(\underset{\mathbf{v^{new}_{AB}} \in VO_{A|B}(\mathbf{v_B})}{\operatorname{argmin}} \left\| \mathbf{v^{new}_{AB}} - \mathbf{v_{AB}} \right\| \right) - \mathbf{v_{AB}} \tag{31}$$

If $\mathbf{v^{new}_A} \in ORCA^{\tau}_{A|B}$ and $\mathbf{v^{new}_B} \in ORCA^{\tau}_{B|A}$, then no collision will occur within τ time. In this case, both A and B bear half the responsibility and remain on a collision-free trajectory. However, as stipulated in the COLREGs, the obligation of taking action in order to avoid a collision between the vessels involved is unequal in different circumstances. Consequently, the concept of ORCA has been generalized accordingly, and the formulation of the generalized ORCA is defined as follows;

Definition 3. Generalized ORCA:

$$gORCA^{\tau}_{A|B} = \left\{ \mathbf{v^{new}_A} \middle| (\mathbf{v^{new}_A} - (\mathbf{v_A} + \eta_{A|B}(1+\sigma)\mathbf{u})) \bullet \mathbf{n} \geq 0 \right\} \tag{32}$$

The region of $gORCA^{\tau}_{A|B}$ (see Fig. 4) is the permitted velocity set for A to avert a collision with B according to the COLREGs rules. Due to the fact that, for both vessels, it will take time to adopt an appropriate maneuver to ensure collision avoidance, we have adapted the smallest change to fit the relative velocity v_{AB} to $(1+\sigma)\mathbf{u}$ required, so that the region of permitted velocity for both vessels is able to guarantee the validity of the collision avoidance maneuver. In Eq. (32) $\eta_{A|B}\Big|\{\eta_{A|B} \in [0,1]\}$ is defined as the obligation reflection parameter of A in order to prevent a collision with B and, for B, the obligation reflection parameter is $\eta_{B|A}\Big|(\eta_{B|A} = 1 - \eta_{A|B})$ with its value being determined by the encounter in question. The specific value of the obligation reflection parameter of both the vessels involved in the potential collision is presented in Table 3. We have adopted disc-shaped agents to illustrate the formation of the generalized ORCA algorithm as shown in Fig. 4, whereas, the proposed algorithm is not, in fact, restricted to the disc-shaped object.

Table 3
The value of obligation refection parameter for different encounters.

Encounter situation	Obligation reflection parameter for vessel A and B
B ↓ / A ↑	$\eta_{A\|B} \in (0,1)$, and the specific value is determined by the maneuverability of vessel A, normally, we set $\eta_{A\|B} = 0.5$ and $\eta_{B\|A} = 1 - \eta_{A\|B}$
B ↙ / A ↑	$\eta_{A\|B} = 1$ and $\eta_{B\|A} = 0$
B ↘ / A ↑	$\eta_{A\|B} = 0$ and $\eta_{B\|A} = 1$
A ↑ / B ↑ / A ↑	$\eta_{A\|B} = 1$ and $\eta_{B\|A} = 0$

4.2. Methodology flow

The specific procedure for our collision detection and avoidance approach is presented in this section and the specific procedure of this approach is shown below, and the computational complexity of presented approach is $O(n)$.

Step 1: *Collision detection*. We must, first of all, calculate the CRI value of the vessels surrounding the USV by adopting the CRI assessment approach noted above. We should then pick out those vessels for which the value of CRI is greater than the collision risk threshold χ, then a priority list should be made in descending order according to the CRI value, with each vessel being marked by its sequence number in the priority list. Consequently, the set of surrounding vessels requires the USV to make a plausible collision avoidance maneuver, which is denoted by $T = \{T_1, \ldots, T_k\}$, where T_1 is the vessel with the highest risk of collision with the USV.

Step 2: *Encounter situation inference*. The encounter situation S^* for each of the vessels in $T = \{T_1, \ldots, T_k\}$ should first be estimated. The corresponding conditions for different circumstance are explained as follows:

- Head-on (denoted by S^h):

$$\begin{cases} B_{T_i} \in [350^\circ, 360^\circ) \text{ or } B_{T_i} \in [0^\circ, 10^\circ] \\ \mathbf{v_U} \bullet \mathbf{v_{T_i}} \leq 0 \end{cases}$$

- Crossing from right (denoted by S^{cr}): $B_{T_i} \in (10^\circ, 112.5^\circ]$.
- Overtaking (denoted by S^O):

$$\begin{cases} B_{T_i} \in [292.5^\circ, 360^\circ) \text{ or } B_{T_i} \in [0^\circ, 22.5^\circ] \\ \mathbf{v_U} \bullet \mathbf{v_{T_i}} \geq 0 \\ v_U / v_{T_i} > 1 \end{cases}$$

- Crossing from left (denoted by S^L):$B_{T_i} \in (247.5^\circ, 350^\circ)$.

If one of these above mentioned conditions of T_i is satisfied, then T_i is considered to be in the related encounter situation, and the threatening vessel is denoted by $T_i(S^*)$.

Steps 3: *The permitted velocity set for USV should be calculated according to the COLREGs*. Firstly, the permitted velocity of the USV by adopting the above presented generalized ORCA algorithm for each threatening vessel in $T = \{T_1(S^*), \ldots, T_k(S^*)\}$ should be restricted, and the corresponding gORCA is $gORCA_{U|T} = \{gORCA_{U|T_1(S^*)}, \ldots, gORCA_{U|T_k(S^*)}\}$. Next, the COLREGs compliant velocity region for each of the vessels in $T = \{T_1(S^*), \ldots, T_k(S^*)\}$ should be calculated.

According to the COLREGs rules, a USV is required to make a starboard maneuver to avoid a situation in which it cuts in front of an oncoming vessel in an S^h, S^{cr} and S^O encounter situation. The region of the velocity satisfying the condition outlined above is presented as follows:

$$C(T_i(S^*)) = \left\{ \mathbf{v} | \mathbf{v} \in gORCA_{U|T_i(S^*)}, s.t. \left[(\mathbf{p}_{\mathbf{T_i(S^*)}} - \mathbf{p_U}) \times (\mathbf{v_U} - \mathbf{v}_{\mathbf{T_i(S^*)}}) \right] \Big|_{\mathbf{z}} > 0 \right\} \tag{33}$$

where the operator $[*]|_{\mathbf{z}}$ denotes the $\mathbf{z}$ component of the vector [31], while $+\mathbf{z}$ is pointing downward in the conventional body-fixed coordinate of the USV. From the definition of $C(T_i(S^*))$, it can be noted that when the velocity of USV is in the region of $C(T_i(S^*))$, the USV will pass the threatening vessel $T_i(S^*)$ safely and avoid cutting in front of $T_i(S^*)$. For other encounter situations, in order to ensure safety, the USV requires no collision avoidance maneuvers unless the other vessel has failed to take an appropriate action so that the permitted velocity set is $C(T_i(S^*)) = gORCA_{U|T_i(S^*)}$.

After making the above calculation, the permitted velocity set for the USV when it is confronted with multiple approaching vessels can be obtained as shown below:

$$C(T) = \left\{ C(T_{1\cdots m}) \middle| C(T_1(S^*)) \cap \cdots \cap C(T_i(S^*)) \cap \cdots \cap C(T_m(S^*)) \neq \varnothing \right\} \tag{34}$$

This means if the intersection set of all the permitted regions of $T = \{T_1(S^*), \ldots, T_k(S^*)\}$ is empty, then the $C(T_i(S^*))$ set should be removed from the tail of $T = \{T_1(S^*), \ldots, T_k(S^*)\}$ until the intersection set is no longer empty.

Step 4: *Choice concerning the ideal maneuver velocity*. Once the constraint set for the permitted velocity of the USV is generated, we can use the following penalty function to obtain the best velocity vector:

$$\mathbf{v}_{\mathbf{U}}^{\mathbf{new}} = \underset{\mathbf{v} \in C(T)}{\operatorname{argmin}} \left\| \mathbf{v} - v_U \frac{\mathbf{p}_{\mathbf{i}}^{\mathbf{goal}} - \mathbf{p_U}}{\| \mathbf{p}_{\mathbf{i}}^{\mathbf{goal}} - \mathbf{p_U} \|_2} \right\|_2 \tag{35}$$

where $\mathbf{p}_{\mathbf{i}}^{\mathbf{goal}}$ is the next near-term waypoint of the USV which can be obtained by adopting a global path approach, and the operator $\|*\|_2$ is the 2-norm of a vector.

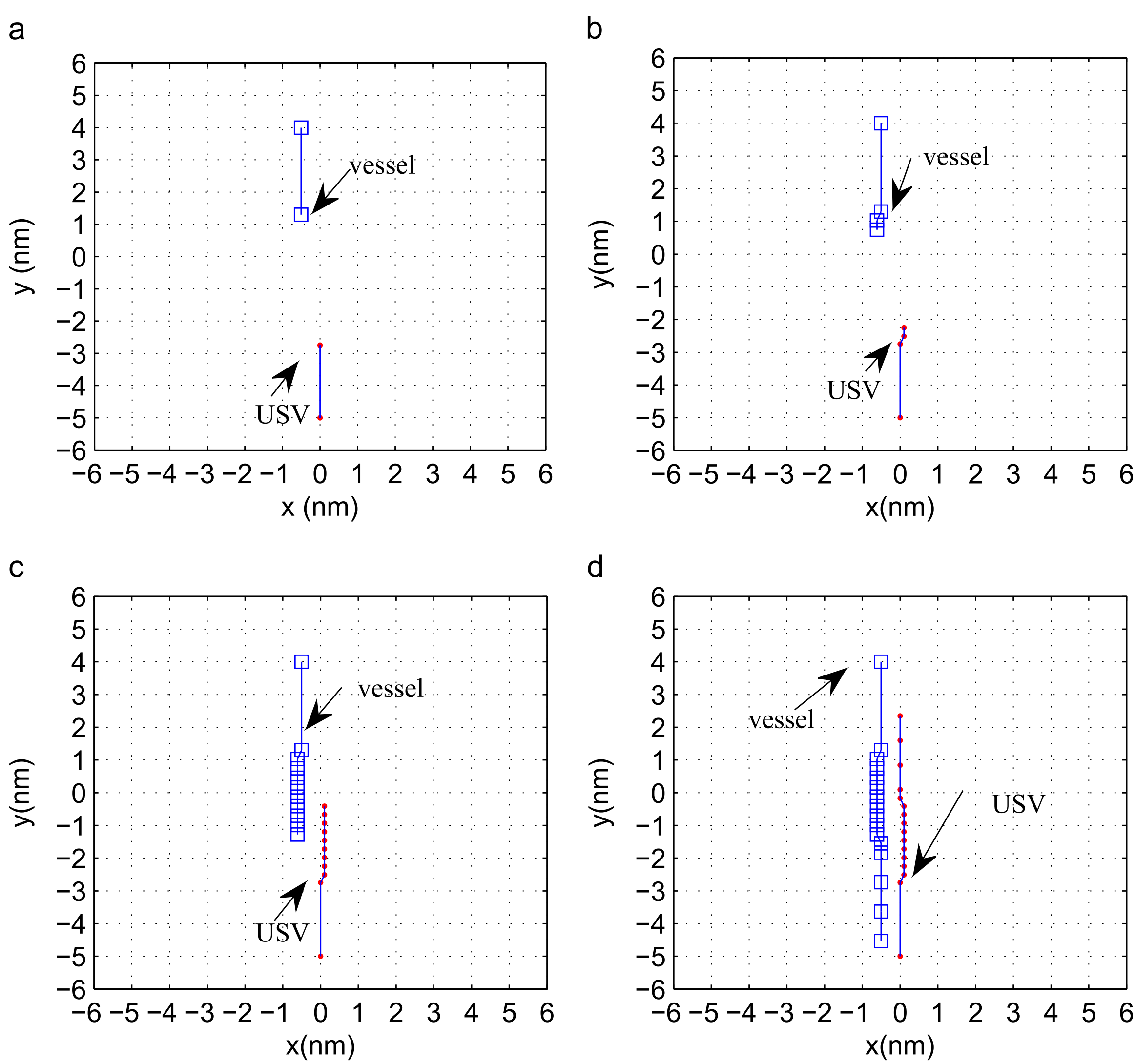

Fig. 5. Head-on scenario.

5. Simulations and discussions

Several standard and complex encounters are investigated here in order to validate the feasibility and effectiveness of our proposed approach for the avoidance of a real-time collision.

Firstly, a standard head-on scenario is simulated to demonstrate the performance of the proposed approach. As shown in Fig. 5(a), both the USV and the target vessel are initially heading towards each other, resulting in a certain collision. When the potential collision is detected, both the vessels should take action so as to avoid the impending collision. According to the COLREGs rules, each one should make a starboard maneuver to pass on the port side of the other vessel. As is shown in Fig. 5(b), once a certain collision risk is confirmed by employing the collision risk detection model of the presented approach, both vessels alter their course accordingly. As long as the value of CRI is under the risk threshold, which means that the collision risk is eliminated, both vessels should alter their course to maintain their original course, as is displayed in Fig. 5(c). Fig. 5(d) shows the successful handling of the head-on encounter by adopting this approach.

The corresponding navigation information for both the USV and the target vessel when a collision is confirmed is shown in Table 4. The initial position of the USV and the target vessel are $(0,-5)$ and $(-0.5,\ 4)$ respectively. The USV is proceeding at a speed of 15 kn and 0° course.

Fig. 6 shows the standard cross encounter situation, where the initial positions of the USV and the target vessel are $(-2,-3)$ and $(3,1)$ respectively, with the USV sailing with a velocity of 16 kn and 0°. As shown in Fig. 6(a), the vessel is crossing to the right of the USV so that a collision will take place unless appropriate measures

Table 4
Information corresponding to the moment when a risk of collision is detected.

Information	Velocity (kn)	Course (deg)	D (nm)	B (deg)	K	CRI
Vessel	18	180	4.08	353	1.2	0.5024

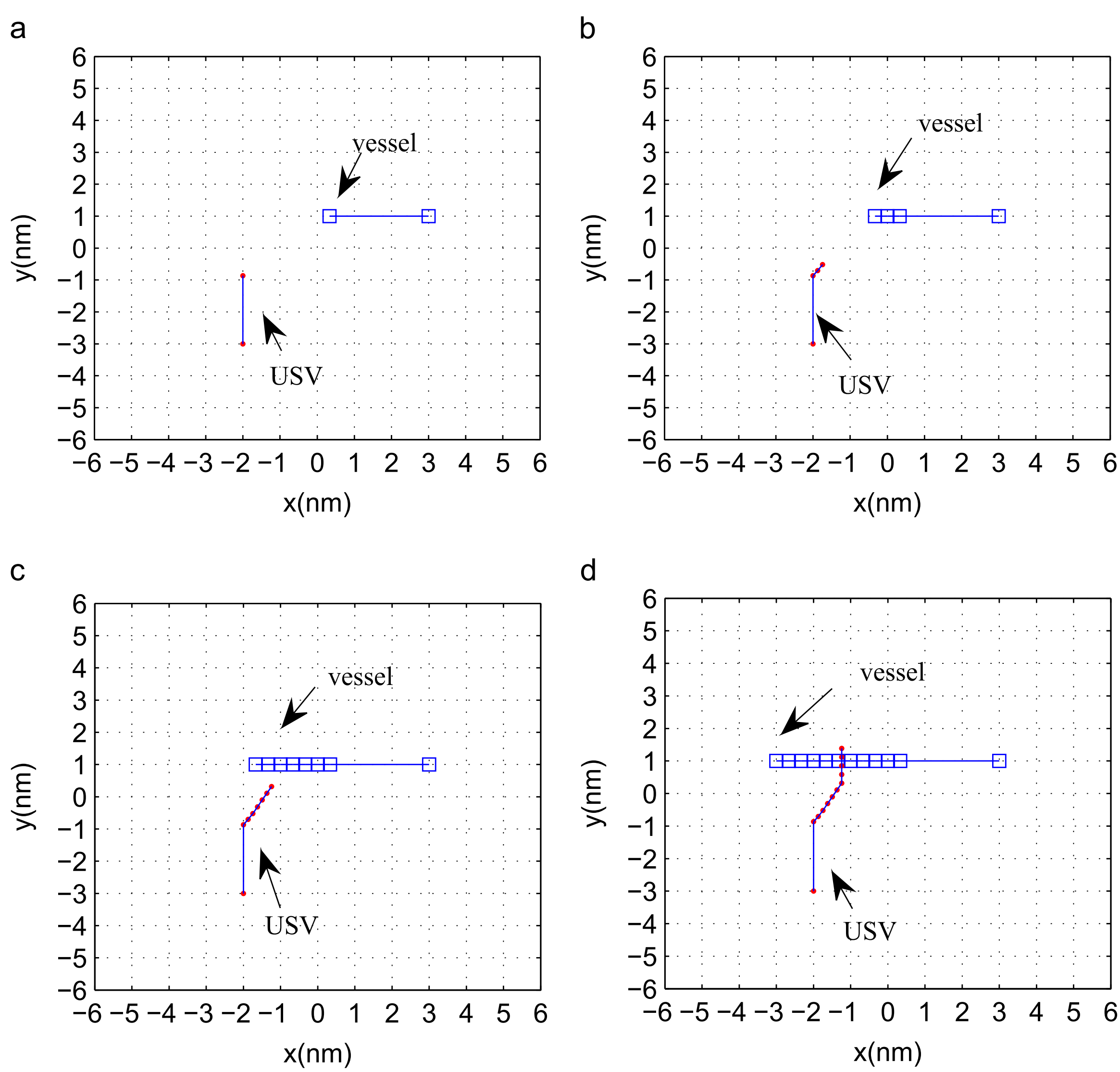

Fig. 6. Scenario in which vessels pass each other.

Table 5
Information corresponding to the moment when a risk of collision is confirmed.

Information	Velocity (kn)	Course (deg)	D (nm)	B (deg)	K	CRI
Vessel	20	270	2.98	51.34	1.25	0.5083

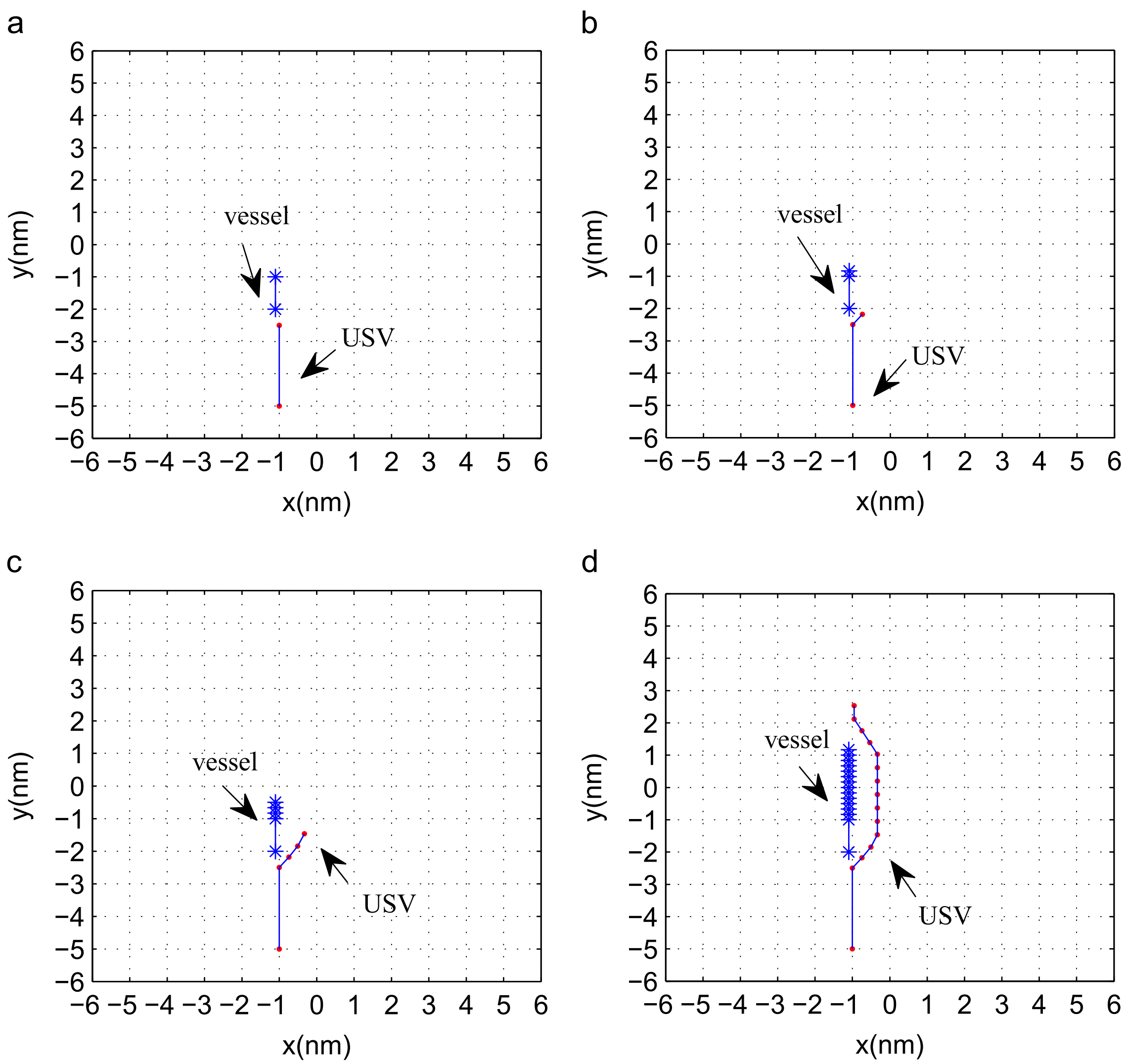

Fig. 7. Scenario in which the vessels overtake one another.

Table 6
Information corresponding to the moment when the risk of collision is confirmed.

Information	Velocity (kn)	Course (deg)	D (nm)	B (deg)	K	CRI
Vessel	10	0	1.503	356.18	0.4	0.5533

to avoid the collision are taken. When the USV moves to $(-2, -1)$ the potential collision is confirmed and the information corresponding to this moment is shown in Table 5; the USV maneuvers starboard to avoid a collision as is shown in Fig. 6(b) while the target vessel maintains its speed and course in accordance with the COLREGs rules. When the vessels move to the position as shown in Fig. 6(c), the value of CRI is updated and under the threshold which means the collision has been successfully avoided by taking the proper action. Fig. 6(d) shows that the two vessels pass each other safely.

As shown in Fig. 7(a), the USV is overtaking the target vessel at a speed of 25 kn, and the initial position of USV and target vessel are $(-1, -5)$ and $(-1.1, -2)$ respectively. According to the COLREGs rules, the USV should take full responsibility for an action to avoid collision. When the potential collision is confirmed, the USV maneuvers starboard to avoid the collision, as illustrated in Fig. 7(b), which complies with the COLREGS rules. The information corresponding to the moment when the collision is detected is shown in Table 6. Fig. 7(c) indicates that the collision avoidance maneuver is effective and reliable. Fig. 7(d) shows that the USV overtakes the target vessel successfully without causing a collision.

As shown in Fig. 8, a complex traffic scenario is simulated to validate the performance of the proposed approach. The initial conditions of the vessels involved are illustrated in Fig. 8(a), which includes most of the standard encounter situation information listed in the COLERGs. For instance, the USV is involved in an encounter with both vessel 2 and vessel 3 in which they will cross one another,

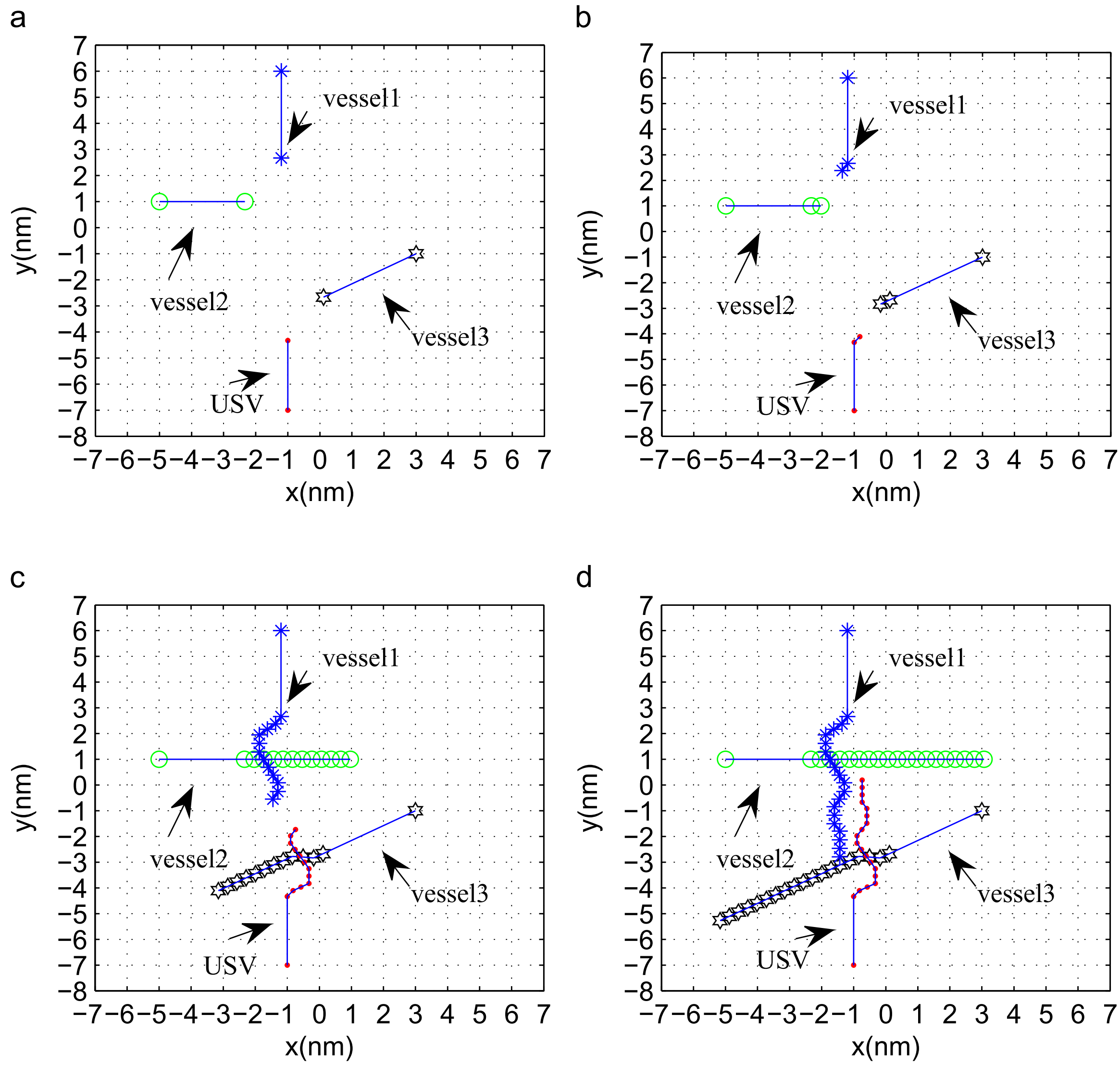

Fig. 8. Complex encounter scenario.

Table 7
Information corresponding to the moment when the risk of collision is confirmed.

Information	Velocity (kn)	Course (deg)	D (nm)	B (deg)	K	CRI
Vessel 1	20	180	7.003	364.51	1.25	0.1258
Vessel 2	18	90	5.497	345.96	1.125	0.1132
Vessel 3	20	240	2.004	33.74	1.25	0.5248

Table 8
Information corresponding to the moment when the risk of collision is confirmed.

	Velocity (kn)	Course (deg)	D (nm)	B (deg)	K	CRI
Vessel 1	20	180	1.769	350.27	1.25	0.5177
Vessel 2	18	90	3.361	27.72	1.125	0.1531
Vessel 3	20	240	2.784	224.37	1.25	0.0644

as well as in a head-on encounter with vessel 1. Fig. 8(b) shows the first time that the USV detects a potential collision with vessel 3; the information corresponding to this instant is shown in Table 7, with Table 7 indicating that vessel 3 has the highest priority in terms of collision avoidance, where the velocity of the USV is 16 kn. In this configuration, vessel 3 crosses the USV from the right, and once the collision risk is confirmed, the USV immediately maneuvers starboard in accordance with the COLREGs so as to avoid cutting in front of vessel 3. Fig. 8(c) illustrates that each of the vessels involved pass each other safely.

When the vessels move to the configuration shown in Fig. 8(c), the USV and vessel 1 form a situation in which there is a danger of a head-on encounter and, after the risk of collision is detected, both the USV and vessel 1 alter their course to avoid a collision.

The information in Fig. 8(c) is shown in Table 8, which indicates that vessel 1 has the highest risk of collision and there is no potential risk of collision between the other vessels. Fig. 8 (b) shows that the proposed approach can interpret the encounter situation correctly and make a decision that is appropriate as well as prompt to avoid collision at the same time as maintaining compliance with the COLREGs rules.

6. Conclusion

A system for the autonomous detection of a collision in real time was presented in this paper and a method for the avoidance of that collision put forward in order to take full advantage of USV in both military and civic applications. The ER theory was utilized first of all to calculate the risk of collision according to the relevant navigation information in order to trigger the prompt alert of a potential collision. A priority list of possible actions was obtained based on the calculation made when an USV is confronted with multiple approaching vessels. Secondly, we extended the ORCA algorithm to determine the maneuver necessary to ensure collision avoidance in keeping with the COLREGs rules. Furthermore, the reactive action of the vessel potentially involved in the collision is also taken into account when making a decision. This conforms to a practical marine situation that is unfortunately ignored in most of the current literature on the subject. A number of simulations were carried out to confirm the validity of the proposed approach. The results of the simulation indicate that the proposed approach is both valid and efficient; constituting a method that would effectively promote the wide application of USV. In future work, the environment conditions will be taken into consideration when making a collision avoidance decision, for instance, the wind, wave and the current. As under some circumstances, they can be taken full advantage to reduce the energy consumption to a large extent.

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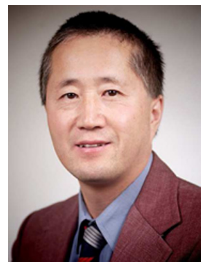

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